Report for 2001GU1343B: Groundwater Infiltration and Recharge in the Northern Guam Lens Aquifer as a Function of Spatial and Temporal Distribution of Rainfall

- Water Resources Research Institute Reports:
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- Conference Proceedings:
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Report Follows:

PROJECT SYNOPSIS REPORT

Project Title:

Responses of well water levels on northern Guam to variations of rainfall and sea level.

Problem and Research Objectives

The island of Guam is blessed with an enormous amount of fresh water stored in the thick limestone mantle that covers almost all of the northern half of the island and some of the southern half of the island. The Northern Guam Lens Aquifer (NGLA) provides 80% of Guam's potable water production of 40 mgd for its 150,000 permanent residents and 1,000,000 tourists who visit the island annually. As limits to production are approached, understanding aquifer characteristics is imperative if the aquifer is to be managed properly to meet future demand and to preserve water quality.

The NGLA is composed primarily of two permeable limestone formations, the Pliocene-Pleistocene Mariana Limestone, and the Miocene-Pliocene Barrigada Limestone (Tracey, et al. 1964). The Mariana limestone was deposited as a shallow-water fringing and barrier reef, and is thickest along the rim of the uplifted northern plateau. The older Barrigada limestone is a deeper-water limestone of bank and off-reef detrital deposits. The Barrigada limestone dominates the interior of the plateau, and accounts for the greatest volume of the aquifer, especially in the phreatic zone and vadose zone of the island's interior. The basement beneath the limestone is a late Eocene-Oligocene submarine volcaniclasitc deposit with a permeability many orders of magnitude less than that of the overlying limestone.

The sustainable yield of the aquifer (which is divided into several independent sub-basins by the complex topography of the underlying basement rock – Figure 1), is not known with sufficient precision to give water managers strict guidelines on where to place wells, and how much should be pumped from each well site. Several areas of uncertainty militate against efforts to determine exactly how to proceed with expanded production in the NGLA. These include an imprecise knowledge of the rainfall distribution over the island – the complexities of which are only now being revealed by Guam's NEXARD weather radar, and new dense raingage networks (Guard 2000). Another uncertainty is the nature of the pathways taken by rainfall through the limestone matrix. Mylorie and Vacher (1999) have proposed a dual-porosity aquifer in which dissolution-widened fractures are typically superimposed on a high-porosity matrix. The conductivity associated with each component is high, though variable, and can be orders of magnitude different from the other. Regional and local conductivity studies show wide-ranging values from 1 - 6 km/day (e.g., Ayers and Clayshulte's (1984) study of tidal-signal attenuation in inland wells) to 1-100 m/day (e.g., local values derived from pumping tests). Contractor and Jenson (2000) modeled the observed properties of well-level variations, and concluded from a comparison of their model results to well-level time series that temporary storage of infiltrating water in the vadose zone is significant and infiltration rates are strongly dependent on the water content of the vadose zone of the NGLA. The optimization of vadose parameters in the model did not achieve appreciable error-reduction in the model's prediction of well level, suggesting that temporal and spatial variations in vadose zone characteristics are insufficiently known and/or that other processes affecting the temporal and spatial distribution of recharge have yet to be discovered. They noted three plausible sources of error; 1) unknown spatial variability of the hydraulic conductivity in the aquifer, 2) unknown variations in evapotranspiration, and 3) large errors introduced, especially under wet conditions, by the dependency of infiltration and storage on precipitation rates on Guam. Continued modeling studies, along with statistical comparison with the historical record and field hydrographic studies were recommended. This paper is an ongoing attempt at the latter. The preliminary results of a study of the rain and tide on three well-level time series are presented.

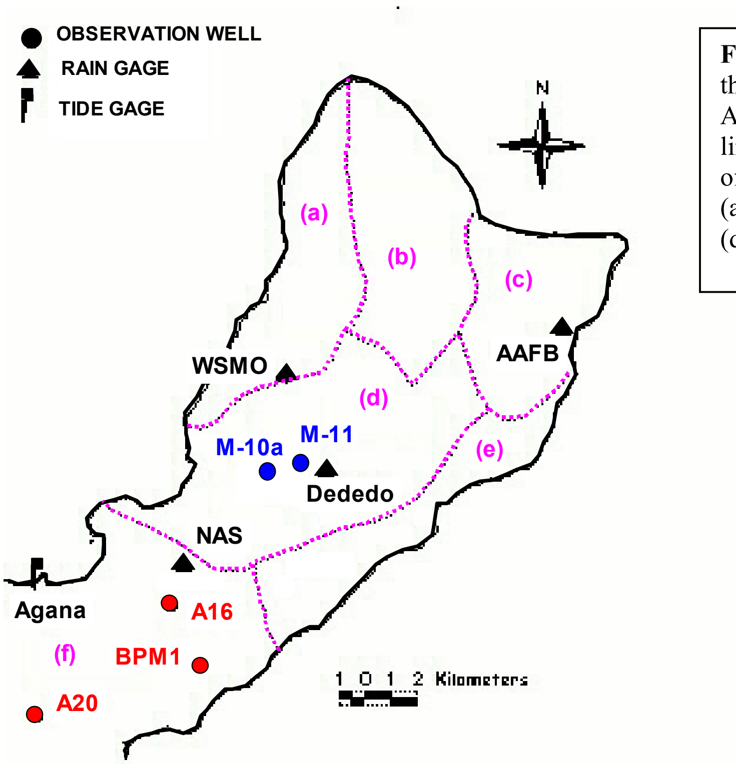

Figure 1. A map of northern Guam showing the locations of cited wells, rain gages, and the Agaña Boat Basin tide gage. The purple dotted lines indicate the boundaries of the sub-basins of the northern Guam lens aquifer: (a) Finagayan, (b) Agafa Gumas, (c) Andersen, (d) Yigo-Tumon, (e) Mangilao, and (f) Agaña.

Methodology

De-tiding the well time series

All well level time series of the NGLA exhibit statistically significant cross-correlations with the time series of the daily average tide (expressed in feet above mean sea level). The tidal signal is transferred rapidly into the aquifer, and cross-correlations are highest at zero time lag for all periods investigated (daily to monthly). At some wells, the variations of sea level account for upwards of 50% of the variance of the time series of daily and monthly average well levels. The correlation of wellheads with the daily and monthly mean sea level is a function of distance from shore.

In order to remove the signal of variations in sea level from the well-level time series, the linear cross correlation value is used. The cross correlation coefficients between the sea level and the level of a given well can be used in a linear regression to predict the value of one variable given the value of the other. The best prediction that a linear regression can yield is given by

$$(A_i)^* = (r) (s_A / s_B) (B_i)' + \overline{A} \tag{1}$$

where: ( )* indicates the predicted value;
( )' indicates departure from the mean value;
subscript i indicates the i^{th} value of the time series;
s_A and s_B are the standard deviations of variables A and B respectively;
r is the cross-correlation coefficient between variables A and B; and,
the over-bar indicates the mean value of the indicated time series.

Using equation (1), the well level may be predicted from the sea-level time series. An adjusted well-level time series that is not correlated with the sea level may be obtained by subtracting the i^{th} term on the right-hand side of equation (1) from the i^{th} raw value of the well-level time series. In this manner, the well-level time series is "de-tided". Note: the well-level time series may be similarly adjusted to "de-rain" the time series, or to remove the component of any variable that has a non-zero cross-correlation with the well level. In this report, the sea level signal was always removed first in order to evaluate the relationship of the remaining "de-tided" time series to the rainfall. Maximum correlations of well level with rainfall tended to occur at a time lag of one of about 1 month with strong evidence that the well heads were also responding to long-term rainfall surpluses and deficits at a long time lag of approximately 18 months. Maximum correlations of well levels with sea level were simultaneous at all frequencies examined.

Using rainfall and tide to predict well levels

The "de-tided" well-level time series may be cross-correlated with any other time series (such as time series of rainfall) to form a multiple linear regression equation of the form:

$$(A_i)^* = (r_{A:B}) (s_A / s_B) (B_i)' + (r_{A:C}) (s_A / s_C) (C_i)' + \overline{A} \tag{2}$$

where: ( )* indicates the predicted value;
( )' indicates departure from the mean value;
subscript i indicates the i^{th} value of the time series;
s_A, s_B, and s_C, are the standard deviations of variables A, B and C respectively;
$r_{A:B}$ is the cross-correlation coefficient between variables A and B;
$r_{A:C}$ is the cross-correlation coefficient between variable A (signal of B removed) and
variable C; and,
the overbar indicates the mean value of the time series.

Such an equation derived to predict the level in well BPM1 from the rain and tide

$$(BPM1_i)^* = 0.5281\,(TIDE_i)' + 0.02227\,(RAIN_i)' + 2.723 \tag{3}$$

yields a predicted time series for BPM1 that explains 66% of the variance of the raw time series. An investigation of the analysis of the variance explained by the rain and the tide (and the inter-relationships among other variables, such as the wind and the tide) at several well sites occurs in a later section.

Integrated anomalies

All of the variables examined in this report (rainfall, the SOI, sea level, and well levels) were subjected to an analysis wherein the long-term annual or monthly mean of the variable is removed and the anomalies of each variable are added in sequence to create a time series of the running total. These running totals, or "integrated anomalies", sharply highlight any long-term deficits or surpluses. The running totals of all the variables show prominent long term deficits and surpluses that are clearly inter-related.

Residuals

One of the most important findings of this study was strong evidence that the wellheads were responding to long-term rainfall surpluses and deficits at a long time lag of approximately 18 months. This property of the behavior of the wellheads was most clearly revealed by analyzing the residuals of the observed wellhead minus the predicted value from the regression equations developed from the sea level and nearly simultaneous rainfall. The time series of the residuals had non-random long-term surpluses and deficits that were clearly related to similar long-term surpluses and deficits of rainfall. The surpluses and deficits in the time series of the residuals best matched those of the rainfall when the rainfall time series was moved forward by 18 months.

Principal Findings and Significance

As the number of tourists and the population of Guam rise, there is an ever-expanding need for potable water. The current rate of production from the NGLA supports 80% of Guam's commercial and residential water needs. The remaining 20% is derived from surface water sources in southern Guam, including the Fena Reservoir and the Ugum River pumping station. Estimates of the sustainable yield of the NGLA show that the current rate of production is nearing it in some sub-basins of the aquifer.

Variations in rainfall and sea level cause variations in well levels (Figure 2). The combined variations in sea level and rainfall in real time or near-real time account for up to 65% of the variance of water levels in the wells – the sea level accounting for the larger share of this variance near the coast, and the rain accounting for the larger share of the variance at well locations further inland. There is evidence that multi-year variations of rainfall appear in the well levels at time lags up to nearly two years. Heavy 24-hour rainfalls of up to 3 inches may cause no immediate response of well levels if they occur at the end of prolonged dryness. Similar rain events cause immediate and large increases of well level if they occur during prolonged wet periods. Rapid increases in well levels in response to heavy short-term rain events decay to background levels within a period of about 10 days. The observed response of the wells to variations in the rainfall and sea level suggest a complicated mix of diffuse and open pathways through a non-homogeneous limestone medium.

A close scrutiny of the well response to the forcing of TIDE and RAIN may help to determine the amount of rainwater captured by the NGLA, and how it travels through the limestone matrix. The mix of time lags at which the wells respond to the RAIN suggest that both the diffuse and open pathways are working to move water through the NGLA independently, with each pathway having its own characteristic distribution and response time. Wells respond to widespread heavy rain events with a sharp spike within one day of an event, then return to pre-event levels after about 10 days. Multi-year surpluses or deficits of rainfall tend to be reflected in the well levels at a nearly 2-year time lag. This 2-year memory of the rain forcing suggests that substantial long-term vadose storage is occurring.

The optimization of vadose parameters in Contractor and Jenson's model (Contractor and Jenson 1999) did not achieve appreciable error-reduction in the model's prediction of well level, suggesting that temporal and spatial variations in vadose zone characteristics are insufficiently known and/or that other processes affecting the temporal and spatial distribution of recharge have yet to be discovered. They noted three plausible sources of error; 1) unknown spatial variability of the hydraulic conductivity in the aquifer, 2) unknown variations in evapotranspiration, and 3) large errors introduced, especially under wet conditions, by the dependency of infiltration and storage on precipitation rates on Guam. The integrated anomalies of the wells used in this report (A16, A20, M10a, M11, and BPM1) (Fig. 2), indicate that ***all*** of the wells in the NGLA are tracking the same long-term forcing, and that each of the wells (except A20) track this forcing in concert. The major surpluses and deficits of integrated well-level anomalies appear to lag by approximately 18 months similar surpluses and deficits in the integrated rainfall anomaly (Figs. 3 and 4) (at A20, the time lag of the response is approximately 6 months). This would suggest that spatial variations in the hydraulic conductivity of the aquifer do not appreciably alter NGLA response to long-term variations in forcing. Future work will examine more wells in the NGLA and extend the time series through the major 1997-98 El Niño episode which should help to address the implications of the well responses to target heavy rain events and to the long-term deficits and surpluses of rainfall.

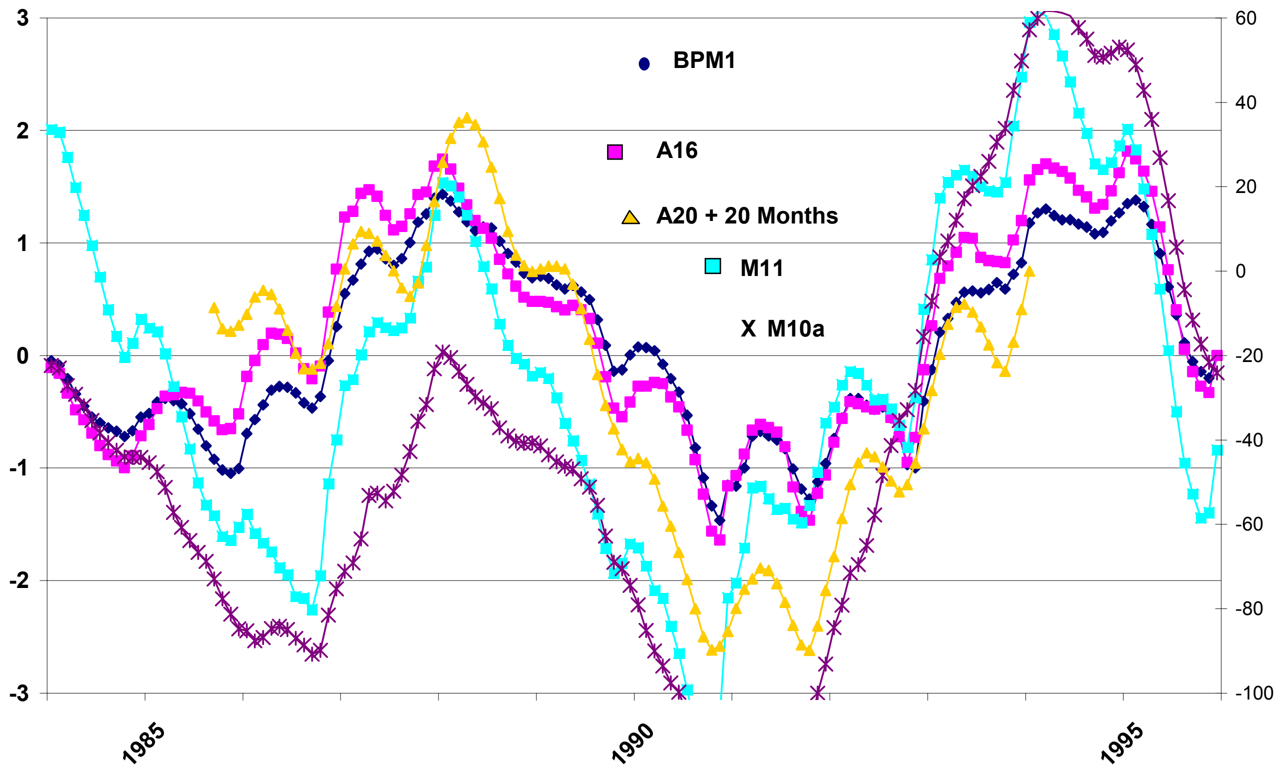

Figure 2. Integrated anomalies of the indicated wells reveal the same long-term trend at each site. All wells rise and fall in concert, except well A20 which exhibits the same rises and falls 20 months earlier (its integrated anomaly has been shifted to the right by 20 months on the chart.

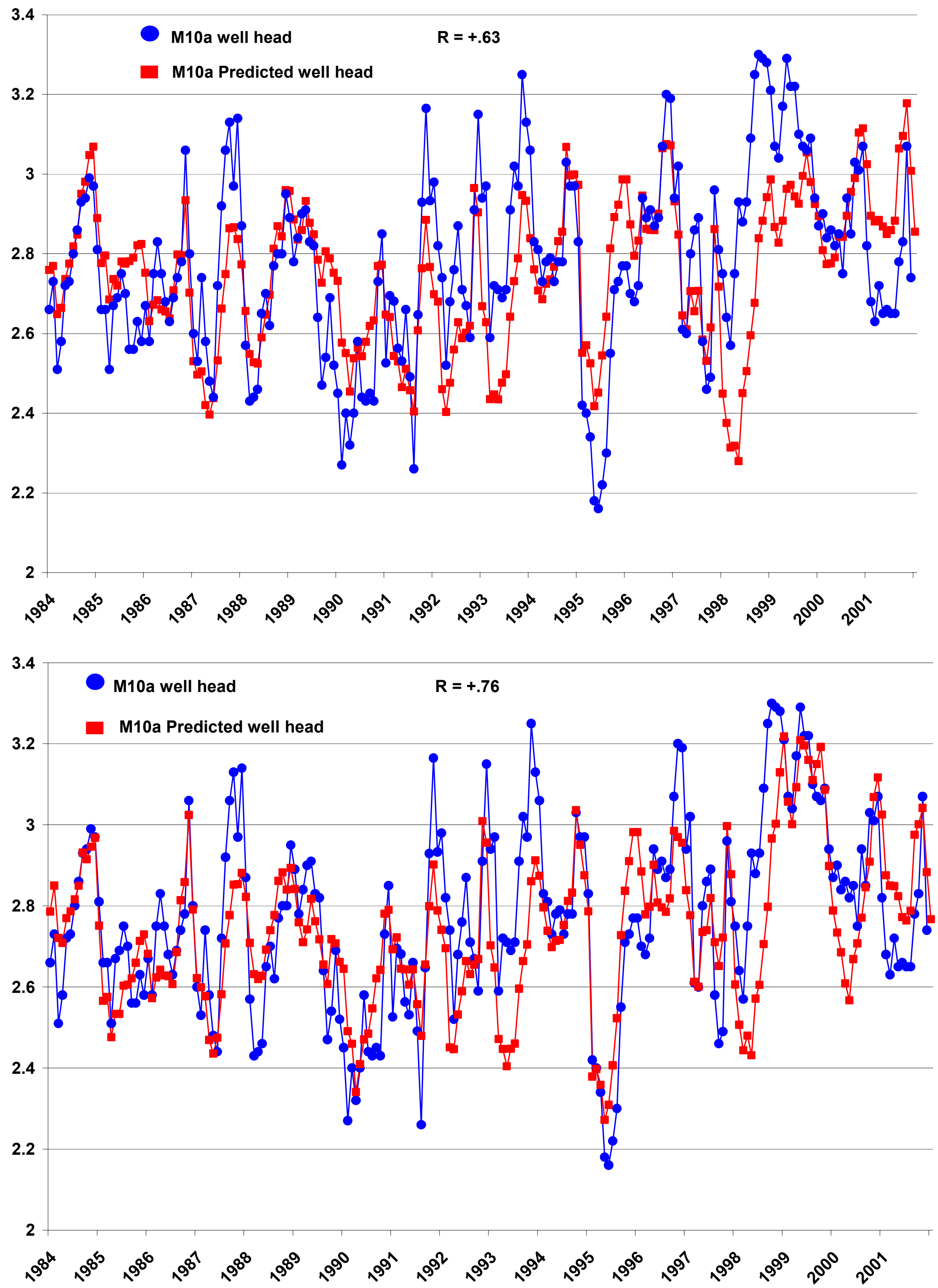

Figure 3. Prediction of the water levels of well M10a based on monthly sea level and rainfall. Top panel shows a prediction made using the sea level and rain anomalies with no time lags. Bottom panel includes a correction made for rainfall at an 18-month time lag. Note the improvement of the correlation coefficient from +.63 to +.76 when the time lag information is included. Blue time series are the observed water level in Well M10a and the red time series are the predictions made from multiple linear regression.

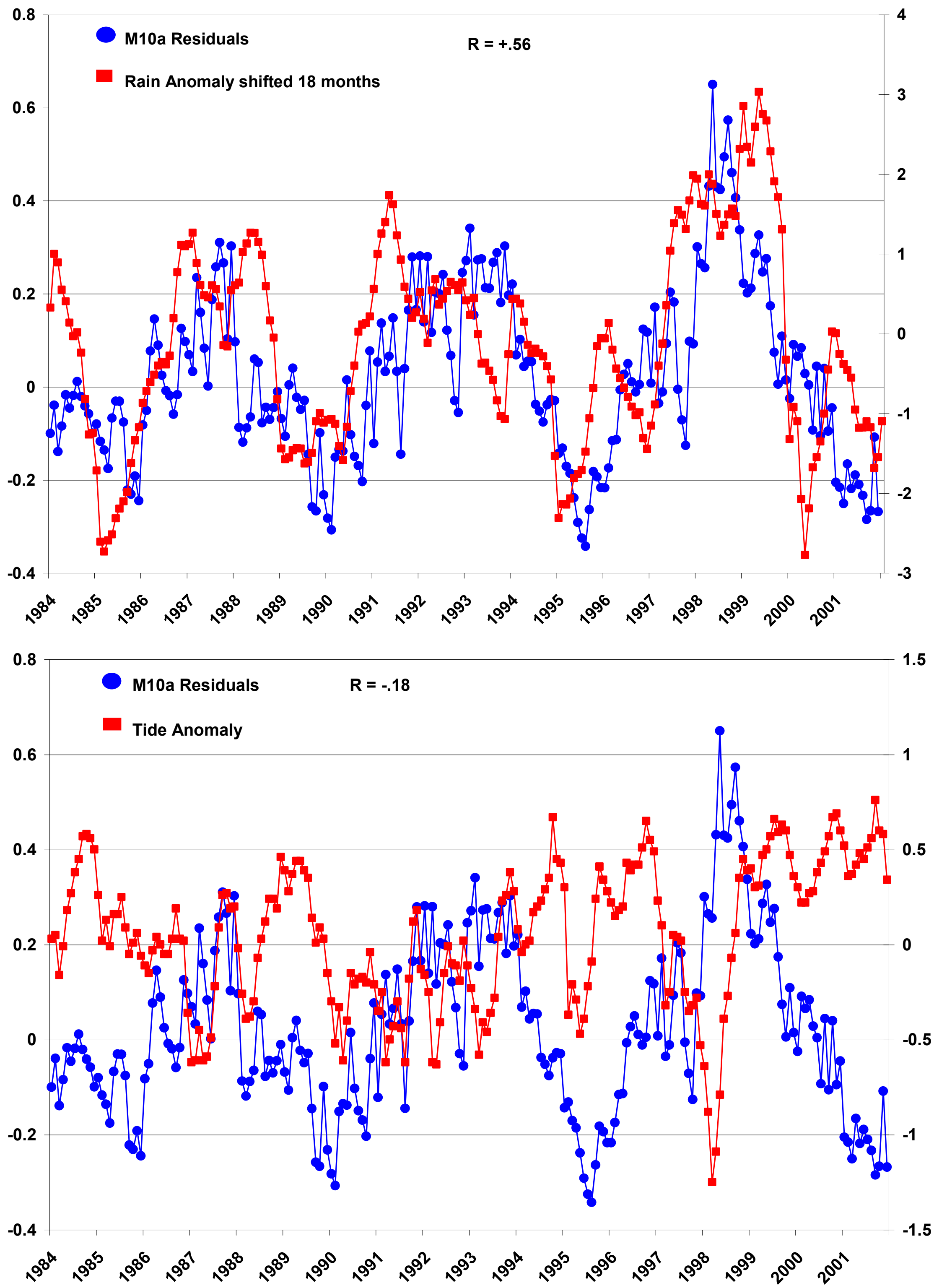

Figure 4. Residuals (observed – predicted) of the time series of the water level in Well M10a. Top panel shows residuals compared with a moving average of the monthly rainfall anomaly that has been shifted forward by 18 months. Bottom panel shows residuals compared with simultaneous sea level anomaly. Note that the non-random surpluses and deficits of the residuals are closely related to rainfall anomalies at an 18-month time lag, but not to sea level in any obvious manner. Residuals are in blue.

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